Energy Dependence of Strangeness Production in Heavy-ion Collision

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Abstract. An experimental overview of the energy dependence of strangeness production is presented. The strange hadrons are considered a good probe to study the QCD matter created in relativistic nucleus-nucleus collisions. The heavy-ion experiments at SPS, RHIC, and LHC have recorded a wealth of data in proton-proton, proton-nucleus and nucleus-nucleus collisions at several beam energies. In this proceeding, I discuss the invariant yield and azimuthal anisotropy measurement of strange hadrons in nucleus-nucleus collisions at SPS, RHIC, and LHC.

1 Introduction

The relativistic heavy-ion collision provides a unique opportunity to study the properties of QCD matter at various temperatures and densities. In order to map out the phase diagram of the QCD matter, experimental programs started in the early 1990s at the Brookhaven Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS) followed by Relativistic Heavy Ion Collider (RHIC) at Brookhaven and recently at Large Hadron Collider (LHC) at CERN. These experiments allowed us to study the QCD matter over a large range of baryonic chemical potential (or net-baryon density) by varying center-of-mass energy($\sqrt{s_{NN}}$) of the two colliding nucleus.

Strange hadron production in nucleus-nucleus collisions is believed to be an important tool to study the dynamics of the produced QCD matter. Due to the large production cross-section of strange quarks in the QGP, an enhancement in the production of strange hadrons in QGP compared to non-QGP medium is expected [1]. Due to low energy density, the matter produced in the nucleon-nucleon (p+p) collisions is considered as a baseline for the non-QGP medium. Production of strange hadrons is being measured in nucleus-nucleus (A+A) collisions and compared with that in p+p collisions to look for any deviation from the non-QGP baseline. Any deviation from the non-QGP baseline would mean the formation of deconfined matter of quarks and gluons in A+A collisions.

Among all strange hadrons, multi-strange hadrons (e.g. ϕ, Ω) are expected to have relatively small hadronic interaction cross-sections and therefore they can carry the information directly from the chemical freeze-out stage with almost no distortion due to late-stage hadronic interaction [2, 3]. The measurement of production yield and azimuthal anisotropy

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of multi-strange hadrons are considered as a useful probe to study the hadronization and collective properties of the QGP medium.

2 Strange Hadron Production

2.1 Transverse momentum (p_T) integrated particle ratio

Test of thermal model:
Figure 1 (the left panel) shows K/π ratios as a function of $\sqrt{s_{NN}}$ in central A+A collision measured at AGS, SPS, and RHIC [4–9]. The K/π ratio is of interest, as it reflects the strangeness content relative to entropy in heavy-ion collisions. The K^+/π^+ and K^-/π^- ratios are shown by red and black symbols, respectively. The observed peak position in the energy dependence of K^+/π^+ has been suggested to be a signature of a change in degrees of freedom [10, 11]. The thermal model calculations are shown as yellow band for K^+/π^+ and green band for K^-/π^- [12–14]. It is shown that the thermal model calculation explains the measured K/π ratios fairly well.

Cannonical Ensemble at high-baryon density:
The ϕ/K^- ratios as a function of $\sqrt{s_{NN}}$ is presented in the right panel of Fig. 1 [15, 16]. The thermal model calculations, based on the Grand Canonical Ensemble (GCE) and Canonical Ensemble (CE) for strangeness with several different choices of strangeness correlation length are shown by different line colors [13, 14]. We can see for $\sqrt{s_{NN}} > 5$ GeV, both GCE and CE calculations explain the data, however for $\sqrt{s_{NN}} \leq 3.0$ GeV GCE calculation under-predicts the measured ϕ/K^- ratios. Calculation using Canonical Ensemble (CE) with strangeness correlation length ~ 3 fm can explain the data measured by STAR and HADES experiment.

Evidence of hadronic rescattering in central A+A collision:
Figure 2 shows K^{*0}/K and ϕ/K ratios as a function of multiplicity in p+Pb and Pb+Pb collisions at 2.76 and 5.02 TeV measured by the ALICE experiment [17]. We see that K^{*0}/K ratios decrease with increasing multiplicity. Whereas the ϕ/K ratio is almost independent of multiplicity. This observation can be understood considering the re-scattering of daughter particles in the hadronic phase. The lifetime of K^{*0} resonance is short (~ 4 fm/c) and therefore they decay inside the fireball. The daughter particles of K^{*0} undergo re-scattering in the hadronic medium and their momentum may get changed. This would lead to a loss in the reconstruction of the parent resonance. The lifetime of the ϕ meson is ~ 42 fm/c. Because of the longer lifetime, the ϕ meson will mostly decay outside the fireball and therefore its daughters will not have much time to rescatter in the hadronic phase. We can also see from Fig. 2 that thermal model calculations, which do not include hadronic rescattering, explain ϕ/K ratios and over-predict K^{*0}/K at the central Pb+Pb collisions. This is a clear piece of evidence of the hadronic rescattering effect on short-lived resonance in central Pb+Pb collisions.

2.2 Particle ratio as a function of p_T

Probing hadronization through baryon-to-meson ratio:
The baryon-to-meson ratios have been predicted to be sensitive to the parton dynamics of the collision system. Figure 3 shows the $\bar{\Lambda}/K_S^0$ ratio as a function of p_T for different centralities in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$–54.4GeV [18]. The enhancement of $\bar{\Lambda}/K_S^0$ ratios at intermediate p_T in central Au+Au collisions compared to peripheral Au+Au at $\sqrt{s_{NN}} \geq 19.6$ GeV is interpreted as a consequence of hadron formation through parton recombination.We do not see any significant difference between central and peripheral collisions for $\sqrt{s_{NN}} \leq$
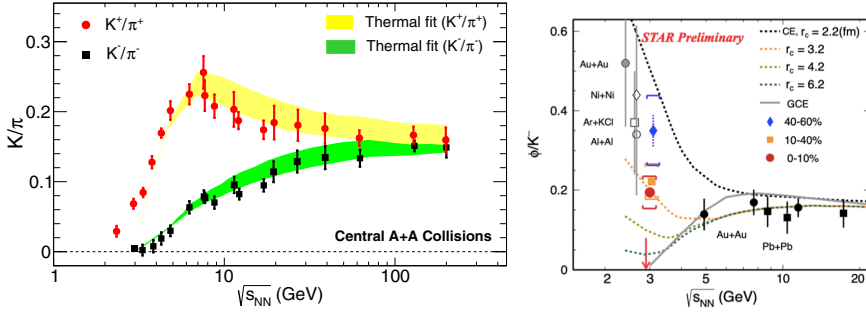
Figure 1. Left panel: The K^+/π^+ and K^-/π^- ratios as a function of $\sqrt{s_{NN}}$ in central A+A collision [4–9]. Right panel: The ϕ/K^- ratios as a function of $\sqrt{s_{NN}}$ [15, 16].
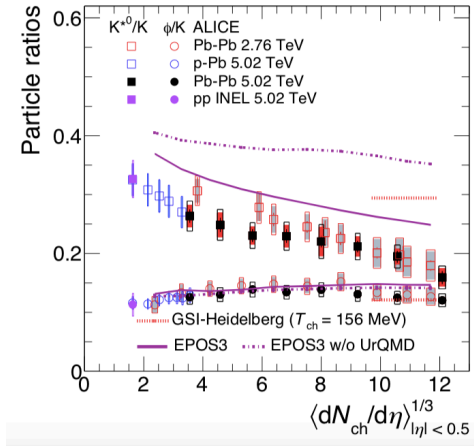

Figure 2. The K^{*0}/K and ϕ/K ratios as a function of multiplicity in p+Pb and Pb+Pb collisions at 2.76 and 5.02 TeV measured by the ALICE experiment [17].

11.5 GeV. This may indicates formation of hadronic interaction dominated matter at $\sqrt{s_{NN}} \leq$ 11.5 GeV.

2.3 Nuclear modification factor

Probing QGP through parton energy loss:

The nuclear modification factor (R_{CP}) is defined as the ratio of the particles yield in the central to peripheral collisions normalized by the number of binary collisions (Nbin). The value of Nbin is calculated from the Monte Carlo Glauber simulation. If R_{CP} is equal to one, then the nucleus-nucleus collision is simply the superposition of nucleon-nucleon collisions. Deviation of R_{CP} from the unity would imply contribution from the nuclear medium effects. The measured R_{CP}, which is less than one at high p_T, at top RHIC and LHC energies indicates the energy loss of partons traversing through QGP medium. Figure 4 show R_{CP} of strange hadrons measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7–54.4GeV [18]. From the Fig. 4 one can see, at the intermediate p_T, R_{CP} goes above unity with the decrease in beam energy. This indicates that at lower beam energy the parton energy loss effect could be less important.
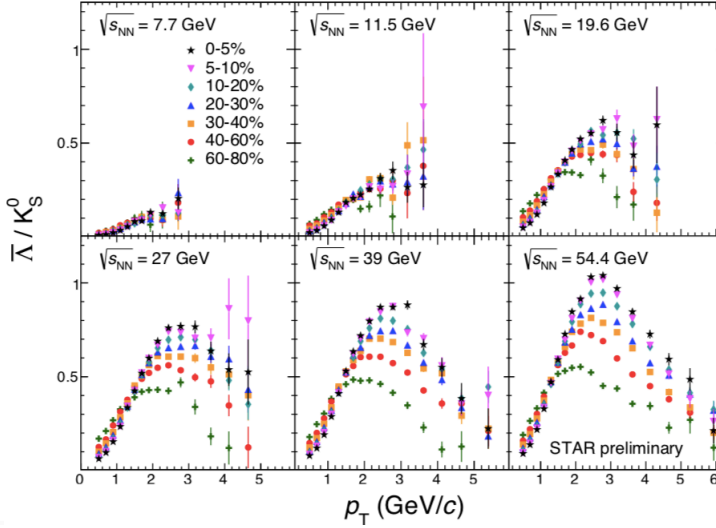
Figure 3. The $\bar{\Lambda}/K_S^0$ ratio as a function of p_T for different centralities in Au+Au collisions at $\sqrt{s_{NN}} =$ 7.7–54.4GeV [18].

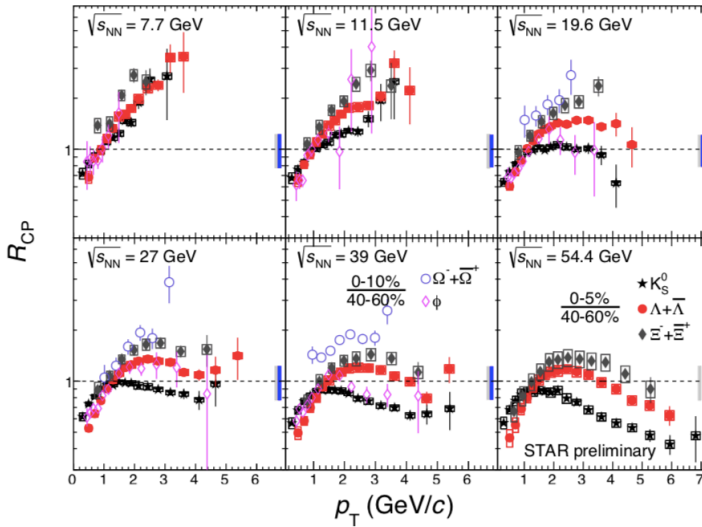**Figure 4.** The nuclear modification factor of strange hadrons measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7–54.4GeV [18].

3 Collective Flow of Strange Hadrons

Partonic collectivity at top RHIC and LHC energies:
Figure 5 shows the v_2 as a function of p_T for π, p, ϕ, and Ω for 0–80% centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and for ϕ, and Λ in 30–40% central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [19, 20]. We see mass ordering in v_2 at low p_T and particle type dependence at the intermediate p_T. The observed mass ordering can be explained by the hydrodynamics

model whereas particle type dependence at the intermediate p_T can be explained through the parton recombination model. It is clear from Fig. 5 that the v_2 of hadrons consisting of only strange quarks (ϕ and Ω) is similar to that of non-strange hadrons π and p. As we know that the ϕ and Ω do not participate strongly in the hadronic interactions unlike π and p, therefore Fig. 5 suggests that the major part of collectivity is developed during the partonic phase at top RHIC energy. This is also true for LHC energies as shown by the ALICE experiment [20].

Turn-off of QGP and change of equation of states ?

The energy dependence of ϕ-meson v_2 measured at intermediate p_T is shown in Fig. 6 [21]. We can see almost constant magnitude ($\sim$0.1) of ϕ v_2 for $\sqrt{s_{NN}} \geq 19.6$ GeV. However, for $\sqrt{s_{NN}} =11.5$ and 7.7 GeV, magnitude of ϕ v_2 is small or close zero within large uncertainties. Small ϕ v_2 is considered as a signature of formation of hadronic interaction dominated matter as ϕ mesons are expected to have small hadronic interaction cross sections. The energy dependence of the slope of ϕ-meson directed flow (v_1) is shown in the right panel of Fig. 6 [22].We see there is indication of ϕ-meson v_1 slope changes sign below $\sqrt{s_{NN}} = 10$ GeV. This could be related to the change of equation of states at the low beam energy. The uncertainties in the current measurement are large, upcoming BES-II program at RHIC is expected to provide precision measurement of ϕ-meson v_1 and v_2.
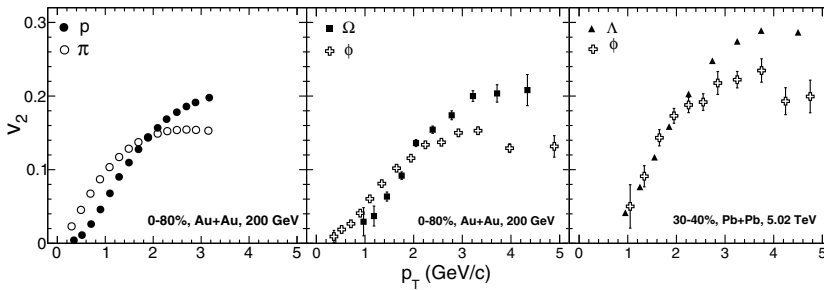

Figure 5. The elliptic flow as a function of p_T for π, p, ϕ, and Ω for 0%–80% centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and for ϕ, and Λ in 30%–40% central Pb+Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV [19, 20].
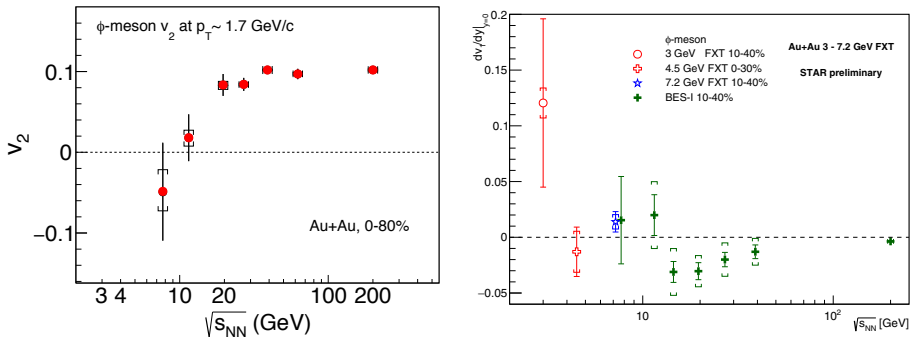

Figure 6. The energy dependence of ϕ-meson v_2 at intermediate p_T and slope of directed flow (dv_1/dy) measured by the STAR experiment [21, 22].

4 Summary

The energy dependence of strange hadron production in heavy-ion collisions is presented. It is found that the thermal model explains the measured particle ratios (e.g. K/π and ϕ/K) and its energy dependence. It has been found that the ϕ/K ratio is a sensitive probe to study the strangeness canonical suppression. We observed thermal model calculations over-predicts K^{*0}/K at the central Pb+Pb collisions. Also, the K^{*0}/K ratio decreases with increasing event multiplicity. This clearly indicates the effect of hadronic re-scattering on short-lived resonance in central A+A collisions. The measured elliptic flow of strange hadrons found to be similar to that of non-strange hadrons at top RHIC and LHC energies, indicating formation of partonic collectivity.

The measure ϕ v_2 at intermediate p_T is found to be close zero within large uncertainties at $\sqrt{s_{NN}}$ =11.5 and 7.7 GeV. The ϕ-meson v_1 slope changes sign below $\sqrt{s_{NN}}$ = 10 GeV. The nuclear modification factor is greater that unity at the intermediate p_T for $\sqrt{s_{NN}} \leq 19.6$ GeV. The baryon-to-meson ($\bar{\Lambda}/K_S^0$) ratios as a function of p_T is found to be centrality independent for $\sqrt{s_{NN}}$ =11.5 and 7.7 GeV. These results indicates formation of hadronic interaction dominated matter below $\sqrt{s_{NN}}$ = 20 GeV.

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